Stability of Backfilled Cross-panel Entries During Longwall Mining

Brad Seymour, Mining Engineer
Doug Tesarik, Mechanical Engineer
Mark Larson, Mining Engineer

National Institute for Occupational Safety and Health
Spokane Research Laboratory
Spokane, WA

Joe Shoemaker, Environmental Specialist

Cyprus Twentymile Coal Company
Foidel Creek Mine
Oak Creek, CO

ABSTRACT

In cooperation with Cyprus Twentymile Coal Co., researchers from the National Institute for Occupational Safety and Health (NIOSH), Spokane Research Laboratory, conducted a study at the Foidel Creek Mine, an underground coal mine near Oak Creek, CO, to evaluate the stability of underground working conditions as a longwall advanced through a series of backfilled cross-panel entries.

Instruments installed in the cross-panel entry pillars, backfill, longwall panel, and adjacent headgate entry were continuously monitored by a computerized data acquisition system as the longwall approached and advanced through the backfilled section of the panel. Data collected from these instruments were analyzed to determine the magnitude and direction of the secondary principal stress changes ahead of the longwall face, deformation and closure of the headgate entry, and stability of the cross-panel entry pillars and backfill. A three-dimensional, boundary element model was calibrated to accurately predict mining-induced stress changes and the distance they occurred ahead of the longwall face.

As the longwall advanced through the backfilled entries, most of the mining-induced load was supported by the cross-panel entry pillars. The backfill provided stability for the roof and floor of the in-panel entries and also confined the entry pillars significantly improving their load-carrying capacity. Comprehensive information derived from backfill material property tests, instrument data, underground observations, and numeric modeling results document the safety and stability of the 8-Right minethrough and should provide beneficial case study information for other longwall backfilling applications in the future.

INTRODUCTION

The Foidel Creek Mine (figure 1), operated by the Cyprus Twentymile Coal Co., is located near Oak Creek, CO, approximately 20 miles southwest of Steamboat Springs. The mine is currently using state-of-the-art longwall equipment to mine low-sulfur, high-quality bituminous coal from an 8.5- to 10-ft- (2.6- to 3-m-) thick coal seam at a depth of about 1,300 ft (396 m). Stable ground conditions and innovative mining equipment, including a 72-in- (183-cm-) wide underground conveyor belt, allow the mine's longwall system to advance at an average rate of 100 ft/d (30 m/d), a rate that recently set world records for longwall production. Because this high-capacity longwall system requires that continuous miners develop gateroads at an average advance rate of 500 ft/day (152 m/d) (Carter, 1996), three parallel 20-ft- (6-m-) wide entries were driven across the 8-Right panel. The panel is 815 ft (248-m) wide by 18,000 ft (5,486 m) long. The cross-panel entries provide access for development of the gateroad entries, as well as escapeways for underground miners.

To maintain the entry stability during subsequent mining of the panel and to eliminate the need for a longwall face change, Cyprus decided to fully support the in-panel entries by backfilling them with an air-entrained mixture of fly ash and cement. The mine requested personnel from the Spokane Research Laboratory of the National Institute for Occupational Safety and Health (NIOSH) to assist in monitoring and evaluating the stability of the panel as the longwall advanced through the backfilled entries.

Prior to this study, Cyprus had obtained information about the local geology (figure 2) from a drill hole in the 8-Right panel. The mine floor is interbedded sandstones, while the immediate roof consists of sandstone and shale sequences. Longwall caving depends primarily on the 24.5-ft- (7.5-m-) thick C sandstone, which forms a cantilever behind the shields 80 to 120 ft (24 to 37 m) before caving (Schissler, 1997). The Wadge coal seam is part

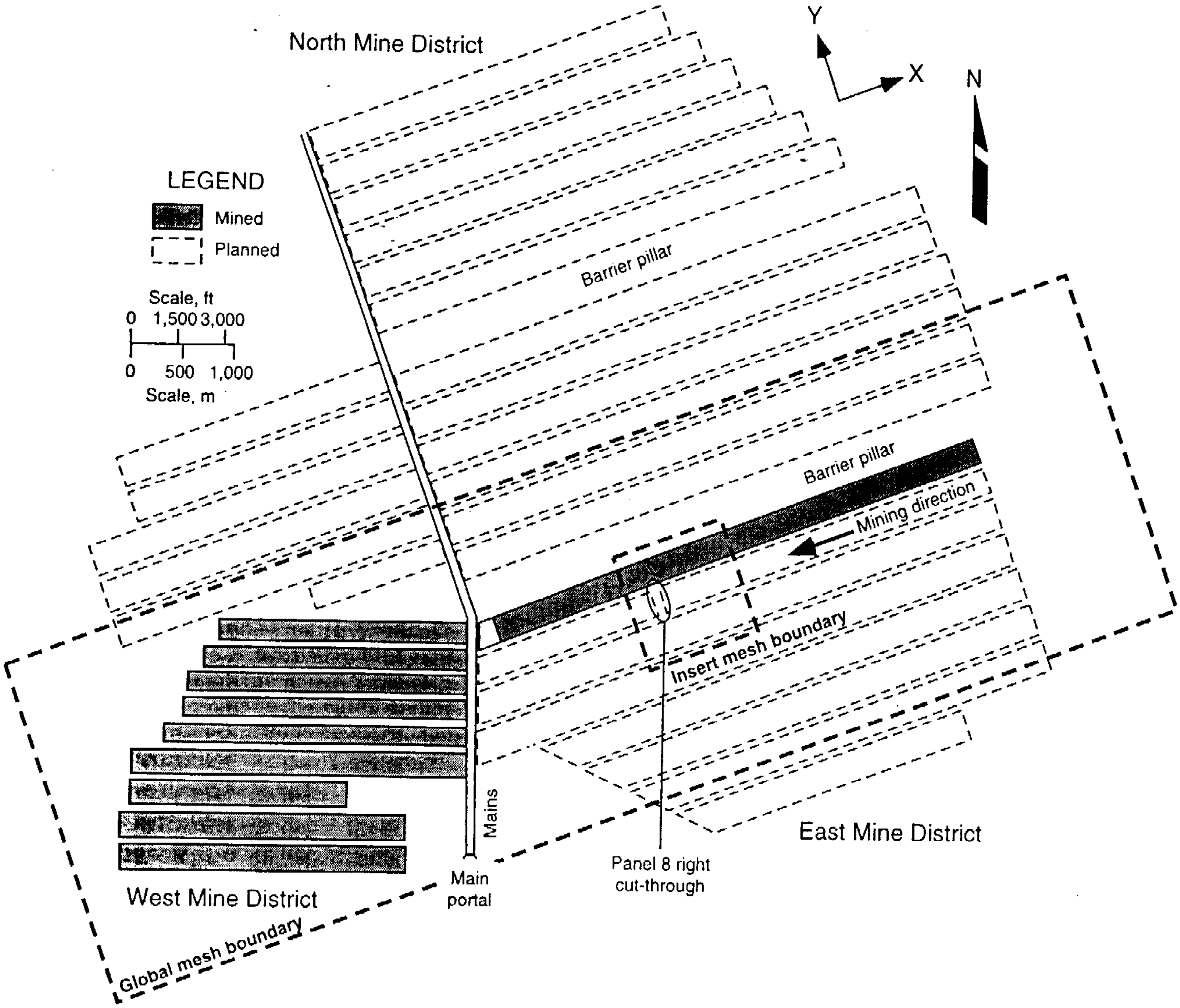

Figure 1.—Plan view of the Foidel Creek Mine.

of the Yampa Coalfield, which crops out along the Yampa River-Williams Fork Mountain area. This seam is a southeastern extension of the Sand Wash structural basin, formed of coal-bearing Upper Cretaceous, Paleocene, and Eocene rocks (Keystone Coal, 1998). The entire area is part of the Green River coal region, which extends from southwestern Wyoming into the northwest corner of Colorado.

BACKFILL PLACEMENT AND MATERIAL PROPERTIES

To maintain the stability of the cross-panel entries during minethrough, the in-panel entries were backfilled by Goodson & Associates, Inc., using a grout mix consisting of fly ash, 10 % cement, and a foaming agent. By entraining air in the mixture, the foaming agent reduced the amount of material required to fill the entries, improved the pumping characteristics of the mix, and reduced problems associated with excess bleed water underground. After bulkheads had been constructed across the tailgate end of the cross-panel entries, the entries were sequentially backfilled over a 3-month period by pumping the grout mix from a surface batch plant down a borehole and through a pipeline set up on the headgate side of the entries. The 8-Right cross-panel entries dipped 5° below horizontal from the headgate to the tailgate, which permitted most of the length of the entries to be gravity-filled tight to the mine roof. Bulkheads were then constructed across the headgate end of the entries, and the remaining portions of the entries were pumped full of grout. The cross-panel entries appeared to be completely filled because no gaps were observed above the fill during mining.

In situ samples of the placed fill were collected in 3- by 6-in (7.6- by 15.2-cm) cylinders as the entries were grouted. The samples were tested to determine compressive strength, apparent modulus of deformation, and tensile strength after 28 and 90 days of curing. Because of inconsistencies in backfill materials, sampling procedures, and/or batching and placement processes, there was considerable variation in the density of the samples, which was reflected in the test results. The average density of the

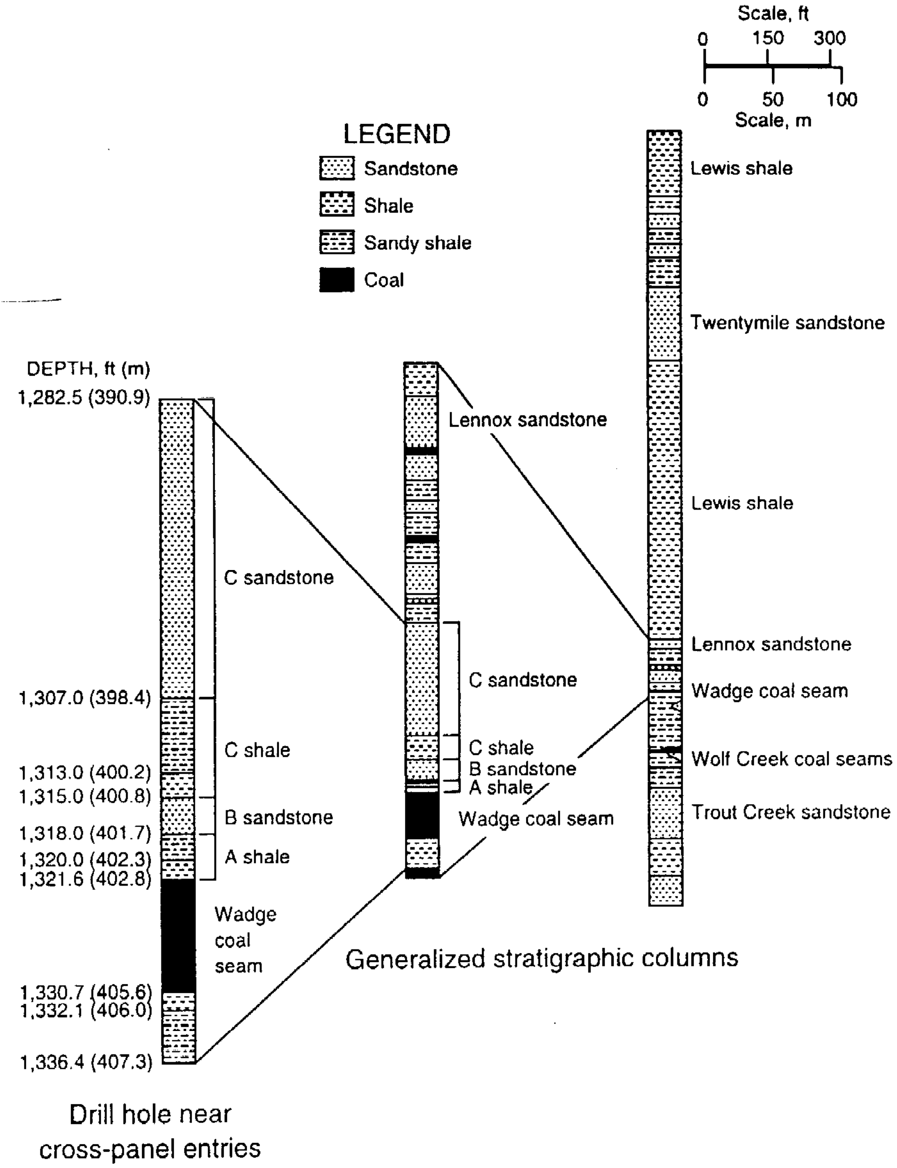

Figure 2.—Stratigraphic column

Table 1.—Summary of backfill test results.

Curing time, days	Compressive strength, psi	Modulus of deformation, psi	Tensile strength, psi
28	199	85,000	22
90	326	104,000	46

compression test specimens was 72.2 lb/ft^3 (1,156 kg/m^3), but the density of individual specimens ranged from 60.5 to 92.9 lb/ft^3 (969 to 1,488 kg/m^3). Generally, the more dense specimens exhibited substantially higher compressive and tensile strengths, as well as higher modulus of deformation values. A brief summary of the backfill test results is given in table 1.

INSTRUMENTS

To monitor stability as the longwall advanced through the backfilled in-panel entries, several kinds of instruments were installed in the cross-panel entry pillars, backfill, longwall panel, and adjacent headgate entry (figure 3). The different types of instruments were clustered in groups to verify readings from individual instruments, to ensure that essential data would be collected if some of the instruments malfunctioned, and to provide additional information for interpreting ground behavior. Most of the instruments (table 2) were equipped with vibrating-wire transducers to minimize the effects of moisture, temperature fluctuations, and cable splices, and also to limit signal degradation resulting from long cable lengths. As the longwall approached and advanced through the backfilled section of the 8-Right panel, the electronic instruments were periodically monitored by a Campbell Scientific data acquisition system stationed in a nearby headgate entry.

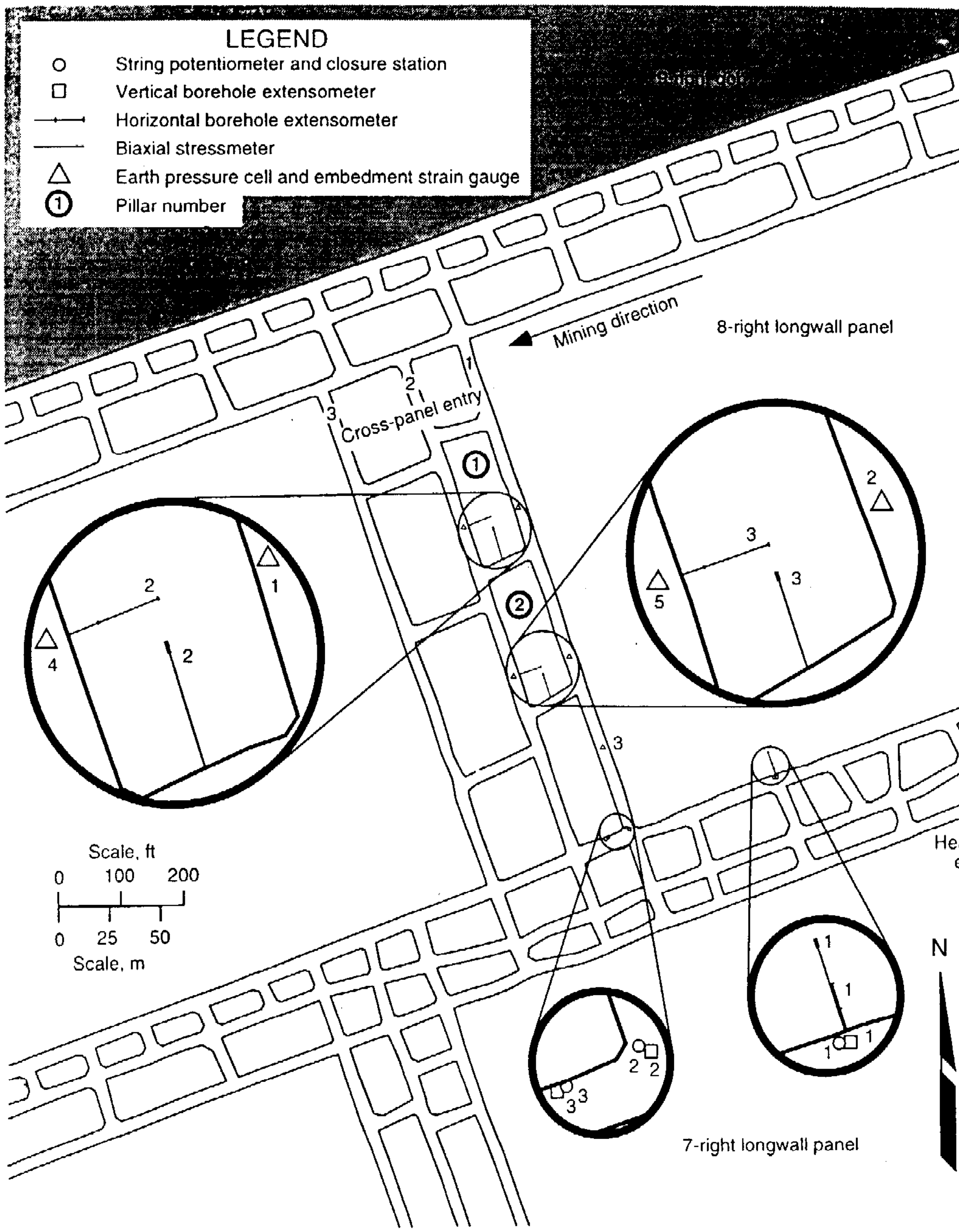

Figure 3.—Plan view of instrument locations.

STRESS REDISTRIBUTION

Longwall Panel and Cross-Panel Entry Pillars

To measure stress redistribution ahead of the advancing longwall, biaxial stressmeters were installed in the 8-Right panel as well as in two of the cross-panel entry pillars (figure 3). Biaxial stressmeters give magnitudes and orientations of the major and minor secondary principal stress changes in a plane perpendicular to the axis of a drill hole by measuring deformation of the drill hole. All stressmeters were equipped with a double set of vibrating-wire gages (two sets of three radial gages oriented 60° from one another, two longitudinal gages, and two temperature sensors) to provide additional data redundancy.

Mining-induced stress changes measured by biaxial stressmeters 1 and 2 are shown in figures 4 and 5 and table 3. Unfortunately, biaxial stressmeter 3, installed in cross-panel entry pillar 2, did not function correctly, probably because of installation problems. Theta, the angle measured clockwise from the major secondary principal stress change (p) to vertical, denotes the orientation of the stress change. For this study, a positive theta angle indicated that the stressmeters were being loaded from the direction of the main entries rather than from the direction of the advancing longwall. As the longwall approached, the orientation of the stress changes measured by biaxial stressmeter 1 was about 10° farther from vertical than the orientation measured by biaxial stressmeter 2. However, stress changes measured by both instruments became more vertical as the longwall approached.

Table 2.—Description of instruments and location.

Instrument	Location	Anchor depth, ft		Dip,[1]	Measurement	Sensor	Position
		1 point	2 point	deg			
BSM 1	8-Right panel rib	39.5		-4.0	Panel stress change	Vibrating wire	Downhole
					Temperature	Vibrating wire	Downhole
BSM 2	Pillar 1	41.8		-5.0	Pillar stress change	Vibrating wire	Downhole
					Temperature	Vibrating wire	Downhole
BSM 3	Pillar 2	40.0		-3.5	Pillar stress change	Vibrating wire	Downhole
					Temperature	Vibrating wire	Downhole
HBX 1	8-Right panel rib	20.24	9.86	0.25	Panel rib dilation	Vibrating wire	Downhole
					Temperature	Thermistor	Panel rib
HBX 2	Pillar 1	37.79	9.88	2.0	Pillar dilation	Vibrating wire	Downhole
					Temperature	Thermistor	Pillar rib
HBX 3	Pillar 2	37.79	9.88	2.0	Pillar dilation	Vibrating wire	Downhole
					Temperature	Thermistor	Pillar rib
VBX 1-3	Headgate entry 1	16.91	4.91	90.0	Roof displacement	Vibrating wire	Downhole
					Temperature	Thermistor	Roof
SPOT 1-3	Headgate entry 1	NA		90.0	Roof-to-floor closure	Rotary potentiometer	NA
CP 1-3	Headgate entry 1	NA		90.0	Roof-to-floor closure	Manual	NA
EPC 1-3	Cross-panel entry 1	NA		0.0	Backfill vertical stress	Vibrating wire	Backfill
					Temperature	Thermistor	Backfill
EPC 4-5	Cross-panel entry 2	NA		0.0	Backfill vertical stress	Vibrating wire	Backfill
					Temperature	Thermistor	Backfill
ESG 1-3	Cross-panel entry 1	NA		90.0	Backfill vertical strain	Vibrating wire	Backfill
					Temperature	Thermistor	Backfill
ESG 4-5	Cross-panel entry 2	NA		90.0	Backfill vertical strain	Vibrating wire	Backfill
					Temperature	Thermistor	Backfill

BSM Biaxial stressmeter. HBX Two-point horizontal borehole extensometer. VBX Two-point vertical borehole gauge. SPOT String potentiometer. CP Closure point station. EPC Earth pressure cell. ESG Embedment strain gauge.

[1]The minus sign indicates negative angle from horizontal.

Table 3.—Stress change versus distance from longwall. Compressive stress is positive.

	Average principal stresses			Longwall distance, ft
	p, psi	q, psi	Theta, deg	
Initial stress change:				
Biaxial stressmeter 1	30	-57	41	991
Biaxial stressmeter 2	31	-51	30	666
Intermediate stress change:				
Biaxial stressmeter 1	131	-68	42	133
Biaxial stressmeter 2	172	-63	31	383
Maximum stress change:				
Biaxial stressmeter 1	790	174	27	7
Biaxial stressmeter 2	1,842	383	23	4
Final stress change:				
Biaxial stressmeter 1	902	258	17	4
Biaxial stressmeter 2	2,140	600	22	4

Stress change values in table 3 were calculated for each instrument by averaging the response of the two sets of radial gages. Final readings obtained from a single set of radial gages on each instrument indicated that the maximum stress change values for p and q were probably higher and oriented closer to vertical.

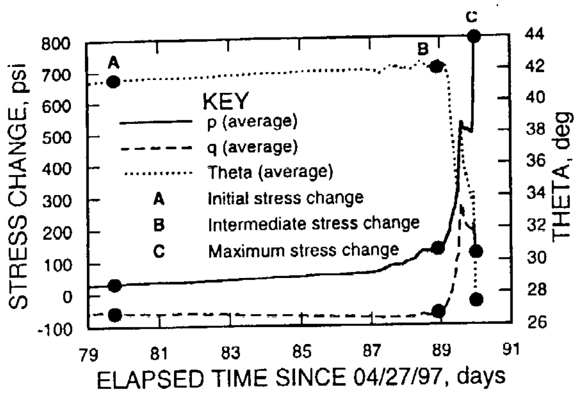

Figure 4.—Stress change in 8-Right panel

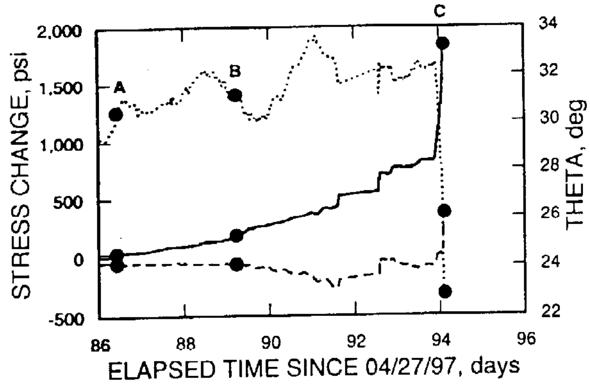

Figure 5.—Stress change in cross-panel entry pillar 1

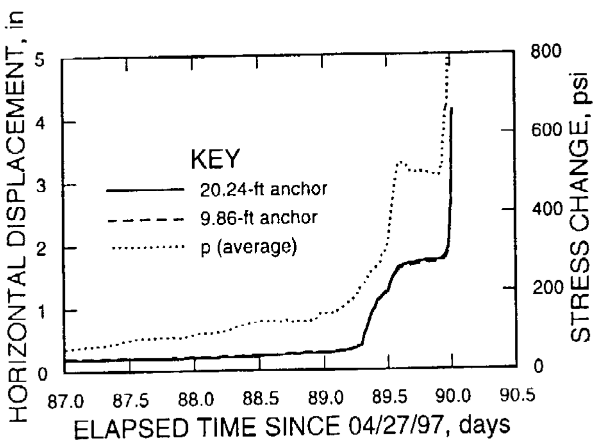

Figure 6.—Dilation and loading of 8-Right panel.

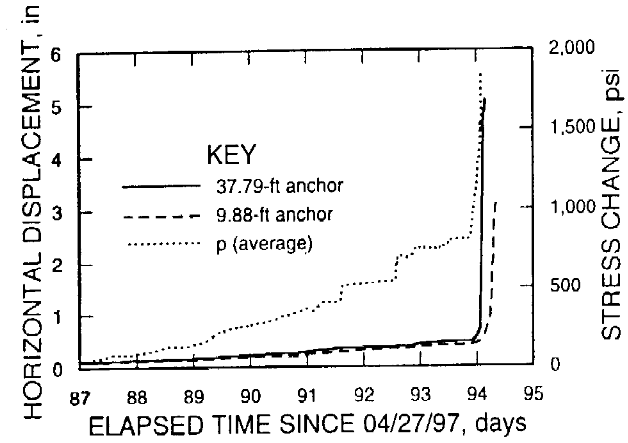

Figure 7.—Dilation and loading of cross-panel entry pillar 1

The stress increases measured by biaxial stressmeters 1 and 2 were verified by two-point horizontal extensometers installed to monitor dilation of the 8-Right panel rib and cross-panel entry pillar 1. Although the horizontal extensometers did not respond to the advancing longwall as early as the biaxial stressmeters, dilation followed the same general trends in stress changes (figures 6 and 7). Dilation measured in cross-panel entry pillar 2 was similar to dilation in entry pillar 1, but horizontal displacements were lower, indicating higher stress in the entry pillars near the tailgate.

Backfilled In-Panel Entries

While the cross-panel entries were being backfilled, earth pressure cells and embedment strain gauges (table 2) were installed at five locations to measure vertical stress and deformation induced within the fill by mining (figure 3). As a general rule, larger vertical stresses were measured in the fill near the tailgate, and much higher stresses were measured in cross-panel entry 2 than in entry 1. During the minethrough of the backfilled entries, maximum vertical stress averaged 182 psi (1.25 MPa) in cross-panel entry 1, compared to 500 psi (3.45 MPa) in entry 2. The maximum vertical response of the earth pressure cells versus distance from the longwall face is shown in table 4.

As additional vertical stress was transferred to the backfilled entries during mining, the backfill strained in compression. Embedment strain gauges installed near each of the earth pressure cells measured these compressive displacements within the fill, confirming loading trends measured by the earth pressure cells. The maximum vertical strain averaged 1.1% in cross-panel entry 1 and 1.4% in entry 2, with larger vertical displacements measured toward the tailgate.

During mining, the backfill had sufficient strength and stiffness to maintain a vertical face and exhibited only minor spalling even when the backfilled entries were exposed along the entire length of the longwall face. Besides providing stability for the roof and floor of the cross-panel entries, the backfill also confined the entry pillars, improving their support characteristics. A comparison of figures 6 and 8 illustrates the importance of this confinement. Whereas the 8-Right panel rib dilated 0.5 in (1.3 cm) when a major secondary principal stress change of about 220 psi (1.52 MPa) occurred, cross-panel entry pillar 1 dilated 0.5 in (1.3 cm) at a stress change of 1,035 psi (7.14 MPa).

Table 4.—Backfill vertical stress versus distance from longwall. Compressive stress is positive.

Stress levels, psi	Earth pressure cells and longwall distance (in parentheses)			
	2	3	4	5
Initial	18 (386)	9 (224)	38 (483)	18 (490)
Intermediate	23 (108)	20 (115)	136 (78)	61 (82)
Maximum	202 ((6)	161 (8)	561 (3)	339 (6)

Because the coal is stiffer than the backfill, most of the mining-induced load was supported by the cross-panel entry pillars rather than the fill. Stress changes measured in the cross-panel entry pillars were much larger than the vertical stress levels measured in the fill (2,140 psi [14.75 MPa] compared to 561 psi [3.87 MPa]). As illustrated by the elapsed time of 92.8 to 93.5 days (figure 8), a stress increase of less than 100 psi (0.69 MPa) was measured in entry pillar 1 as the longwall advanced through the first cross-panel entry. Minimal stress changes were recorded between days 89.6 and 89.8 (figure 6) and 93.6 and 93.8 (figure 8) and corresponded to utility shifts when the longwall was idle. Although the in-panel entry pillars appeared to be less stable than the 8-Right panel, no alarming stability problems were observed.

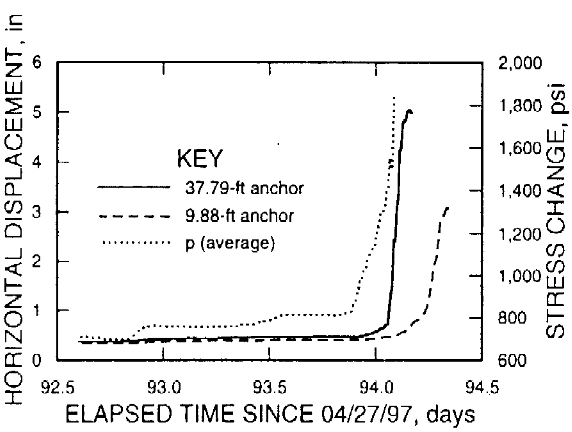

Figure 8.—Dilation and loading of cross-panel entry pillar 1 during minethrough.

HEADGATE ROOF BEHAVIOR

To monitor the stability of the adjacent headgate entry, closure stations were installed at three locations in headgate entry 1 between the conveyor belt and the 8-Right panel rib line (figure 3). Each closure station contained a string potentiometer and a set of closure points. The string potentiometer monitored roof-to-floor closure continuously, and the closure points allowed manual measurements to be taken periodically to verify the electronic readings. Near each closure station, a two-point vertical borehole extensometer was installed overhead to measure relative vertical displacements in the overlying B and C sandstones (figure 2). These instruments measured less than 1.65 in (4.19 cm) of roof-to-floor closure and less than 0.14 in (3.56 mm) of vertical displacement in the first 17 ft (5.18 m) of the mine roof, indicating that the headgate entry was very stable during minethrough. The minimal movement could be explained as the result of the following: the instruments had to be located less than 4 ft (1.22 m) from the panel rib line; the headgate entry roof was well supported by roof bolts, mesh, and trusses; intersections with the in-panel entries were supported by wooden cribs prior to minethrough; and additional roof support was provided by the longwall gateroad shields. The instruments installed in the intersection of cross-panel entry 1 indicated that less than 8% of the measured roof-to-floor closure could be attributed to strata separation in the immediate mine roof. Therefore, most of the roof displacement appeared to occur above the C sandstone horizon.

UNDERGROUND TEMPERATURE

All electronic instruments except the string potentiometers were equipped with a temperature sensor (table 2). As expected, very little change in temperature was measured at depth within the coal. Downhole temperature sensors on the biaxial stressmeters indicated an average temperature change of less than 1.2°F (0.7°C). By comparison, the temperature sensors positioned near the roof and rib of headgate entry 1 were more exposed to the mine's ventilation circuit and, consequently, recorded larger fluctuations in temperature, particularly as the longwall passed by (figure 3). For example, the thermistors, which were mounted in the caps of horizontal extensometer 1 and vertical extensometers 1 and 2, measured an average temperature change of 5.2°F (2.9°C). Although all of the temperature sensors in the headgate entry displayed a similar response to fluctuations in the mine's ventilation system, the thermistor installed with vertical extensometer 3 measured an overall temperature change of 11.4°F (6.3°C).

The largest temperature changes were measured in the backfill and resulted from the heat of hydration as the fill cured. As the in-panel entries were backfilled, the thermistors on the earth pressure cells and embedment strain gauges recorded an average temperature increase of 49.5° and 68.1°F (27.5 and 37.8°C), respectively. Generally, the instruments installed adjacent to cross-panel entry pillar 2 near the center of the 8-Right panel measured greater temperature changes than instruments installed toward the tailgates or headgates, and the instruments installed in cross-panel entry 2 measured higher temperatures than those installed in cross-panel entry 1 (figure 3). While the thermistors on the earth pressure cells and embedment strain gauges measured an average maximum temperature of 112.0 and 131.1°F

(44.5 and 55.0°C), respectively, backfill temperatures may have reached as high as 136.2°F (57.9°C) as indicated by embedment strain gauge 5.

NUMERICAL MODELING

The three-dimensional, boundary-element program BESOL (Crouch Research, 1986) was used to model how mining in the West Mine District and the 9-Right panel affected the 8-Right panel. In plan view, this model represents a 36,000- by 10,800-ft- (10,973- by 3292-m-) section of the mine that includes some of the North Mine District as well as most of the West and East Mine districts (figure 1). Material property inputs for BESOL (table 5) were based on laboratory (Schissler, 1997) and field (Beckett and Madrid, 1986) studies and consisted of determining elastic modulus and Poisson's ratio for the host rock, coal seam, backfill, and gob. To account for variations in the fly ash and other factors, such as settling of solids during backfilling, the modulus for the backfill was reduced to approximately 60% of the 28-day value listed in table 1.

Results from the global BESOL model indicate that there is a vertical stress gradient in the 8-Right panel caused by mining the 9-right panel. Stress redistribution from the West Mine District to the 8-Right panel extended from the mains 800 ft (243.8 m) inby or 5,800 ft (1767.8 m) outby 8-Right cross-panel entry 3.

To analyze the effects of mining the 8-Right panel on the backfilled cross-panel entries and in-panel entry pillars, a mesh was constructed that consisted of 180 by 180 elements and represents a 3,600- by 3,600-ft^2 (1097- by 1097-m^2) area (figure 1). Adjustments were made in the material properties used in the model until the predicted stress changes were reasonably close to the stress changes measured by the biaxial stressmeters and earth pressure cells. This process involved reducing the coal modulus and using a nonlinear stress-strain curve to model the gob.

$$\sigma = \frac{a\,\epsilon}{(b - \epsilon)} \qquad (1)$$

where σ = normal stress, psi

$a = 1500$,

ϵ = normal strain,

and $b = 0.02$.

Regression analyses on predicted versus measured stress changes produced correlation coefficients of 0.91 and 0.78 for the biaxial stressmeters and earth pressure cells, respectively. The stress path predicted for biaxial stressmeter 2 nearly duplicates the stress path produced from measured stress change values (figure 9). However, BESOL predicted higher stress changes for biaxial stressmeter 1 (figure 10). The data for both stressmeters indicated that the model accurately predicts the distance from the longwall face over which a stress increase occurs.

Stress changes measured by earth pressure cell 4 (figure 3) and stress changes predicted by the BESOL model were nearly identical until the longwall face was approximately 30 ft (10 m) from the instrument (figure 11). The two values diverged as the stress change exceeded the laboratory 90-day unconfined compressive strength of the backfill. Although the model generally predicted higher stresses than were measured in the backfill, it accurately predicted the distance from the longwall that stress increases occurred in the fill.

Secondary principal stress angles calculated from stress changes predicted by BESOL varied a maximum of 13° from theta angles measured by biaxial stressmeter 2. If excess horizontal stresses from earlier measurements (Bickel and Donato, 1988) are added to the initial stress state in the numerical model, this difference is reduced to 7°. Theta decreased in magnitude as the longwall approached the instrument.

Table 5. BESOL Material Properties.

	Mine-wide model	8-Right model
Rock modulus, psi	1.1×10^6	1.1×10^6
Rock Poisson's ratio	0.25	0.25
Backfill modulus, psi	50,000	40,000
Backfill Poisson's ratio	0.3	0.3
Gob modulus, psi	5,000	Nonlinear: from 75,757 psi at 8 psi applied load to 208,346 at 1,000 psi applied load.
Gob Poisson's ratio	0.3	0.3
Coal modulus, psi	400,000	150,000
Coal Poisson's ratio	0.3	0.3
Overburden weight, lb/ft^3	155	155

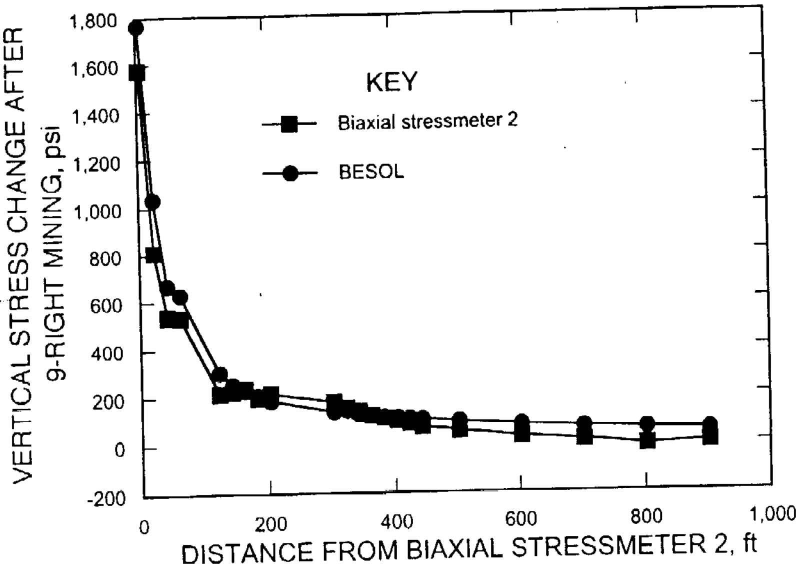

Figure 9.—Comparison of predicted and measured stress changes for cross-panel entry pillar 1.

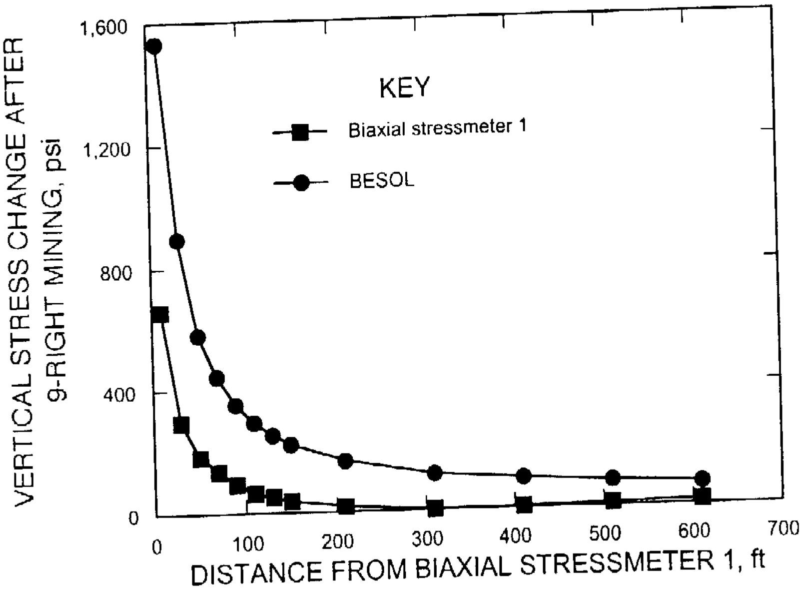

Figure 10.—Comparison of predicted and measured stress changes for the 8-Right panel.

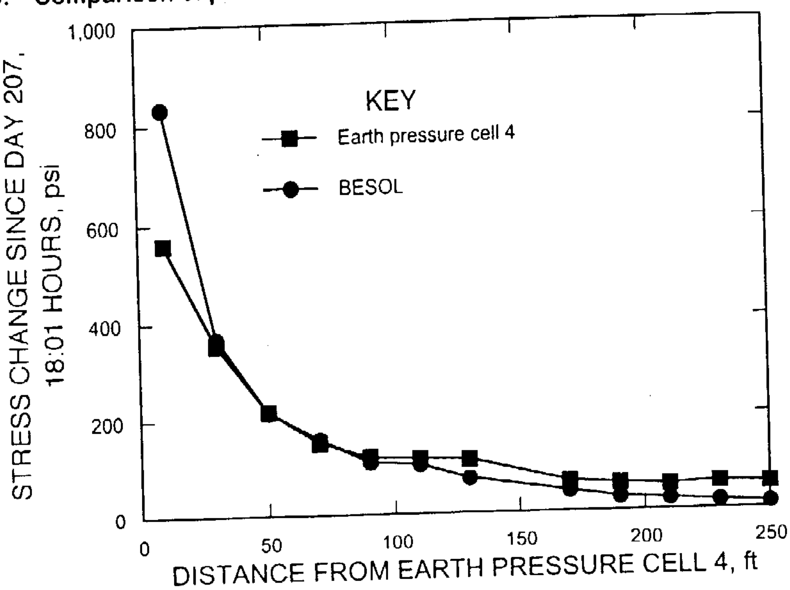

Figure 11.—Comparison of predicted and measured stress changes in cross-panel entry 2.

CONCLUSIONS

Biaxial stressmeters proved to be reliable for measuring the magnitude and direction of mining-induced stress changes ahead of the longwall face. As the longwall approached and advanced through the backfilled section of the 8-Right panel, much higher stress increases were measured in the in-panel entry pillars than in the longwall panel. A stress increase of 2,140 psi (14,75 MPa) was measured in the center of the first cross-panel entry pillar compared with a stress increase of 902 psi (6.22 MPa) approximately 240 ft (73 m) inby the first backfilled in-panel entry. The major secondary principal stress changes were oriented from the direction of the main entries approximately 20° from vertical. The front abutment stress extended 133 ft (40 m) ahead of the longwall as it advanced through the 8-Right panel and 382 ft (116 m) as the longwall approached the in-panel entry pillars. Backfill vertical stresses did not increase substantially until the longwall was 101.5 ft (30.9 m) from the first cross-panel entry and 70 ft (21 m) from the second entry.

During the minethrough, vertical stresses in the backfilled entries ranged from 161 to 561 psi (1.11 to 3.87 MPa). In general, higher stresses were measured toward the tailgate of the entries, and higher stress levels were measured in the second cross-panel entry than in the first entry. These loading trends were confirmed by vertical displacement measurements within the fill. Although most of the mining-induced load was supported by the cross-panel entry pillars rather than by the fill, pillar dilation measurements verified that the backfill confined the entry pillars, significantly improving their load-carrying capacity.

The adjacent headgate entry was very stable during the minethrough, and most of the measured roof movement occurred above the C sandstone. While only small temperature changes were measured at depth within the coal and along the roof and rib of the headgate entry, higher temperatures were generated by the heat of hydration of the cement and fly ash in the backfill. As the placed fill cured, temperatures may have reached as high as 136°F (58°C).

Stress change measurements were used to validate a three-dimensional, boundary-element model representing the instrumented section of the 8-Right panel. The stress changes predicted by the model were consistent with stress changes measured by instruments installed in the longwall panel, cross-panel entry pillars, and backfilled entries. The model also accurately predicted the distance from the longwall face that mining-induced stress changes would occur in the coal and backfill.

The combined use of laboratory tests, instrument data, underground observations, and numerical modeling provided comprehensive information about ground behavior, rock and backfill properties, and performance of the fill, as well as the stability of the backfilled section of the 8-Right panel during minethrough. Stresses measured ahead of the longwall face are similar to the range of stresses reported for the panel, backfill, and in-panel entry pillars during a similar minethrough of backfilled entries at the Emerald Mine in Pennsylvania (Chen et al., 1997). By documenting the safety and stability of the 8-Right panel minethrough, this study should lead to further successful longwall backfilling applications.

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